Neutrino physics beyond neutrino masses

F. del Aguila[*], **J. de Blas**[**], **A. Carmona**[***], and **J. Santiago**[†]
CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain

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We briefly summarise the current status of neutrino masses and mixing, paying special attention to the prospects for observing new leptonic interactions.

1 Introduction

The observed neutrino properties are in agreement with the minimal extension of the Standard Model (SM) resulting from the sole addition of neutrino masses [1, 2]. Neutrinos are massless within the SM because there are not neutrino singlet counterparts, Higgs fields transform as an electroweak doublet, and the theory is renormalizable in the old sense. However, neutrino masses are generated relaxing any of these three conditions. Indeed, the addition of three right-handed (RH) neutrinos ν_R allows for arbitrary Dirac neutrino masses after electroweak symmetry breaking, $<\phi^0>= v/\sqrt{2}$,

$$-y^\nu_{\alpha\beta}\overline{l^\alpha_L}\tilde{\phi}\nu^\beta_R + \text{h.c.} \to -y^\nu_{\alpha\beta}\frac{v}{\sqrt{2}}\overline{\nu^\alpha_L}\nu^\beta_R + \text{h.c.}\,, \quad \text{where } l = \begin{pmatrix} \nu \\ \ell \end{pmatrix} \text{ and } \tilde{\phi} = i\sigma_2\phi^*\,, \tag{1}$$

similarly as for up quarks but with Yukawa couplings $y^\nu_{\alpha\beta}$ much smaller. This lepton number conserving (LNC) term and the corresponding neutrino mass matrix then provide the observed neutrino masses and charged current mixing upon diagonalisation,

$$m_{\nu i} = U^\dagger_{Li\alpha}y^\nu_{\alpha\beta}\frac{v}{\sqrt{2}}U_{R\beta i}\,, \quad \text{with } U_{L,R} \text{ unitary matrices, and} \tag{2}$$

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\,\overline{\ell^\alpha_L}\gamma^\mu U_{L\alpha i}\nu^i_L W^-_\mu + \text{h.c.}\,. \tag{3}$$

Neutrino oscillations, which is the only manifestation of neutrino masses and mixing up to now, are well described by two mass splittings $\Delta m^2_{ij} \equiv m^2_{\nu i} - m^2_{\nu j}$ and the PMNS mixing matrix [3], which equals U_L when l^α_L are written in the charged lepton mass eigenstate basis. A global fit to available data gives [4]

$$\begin{array}{r} \Delta m^2_{21} = 7.67^{+0.67}_{-0.61}\times 10^{-5}\text{eV}^2, \\ \Delta m^2_{31} = \begin{cases} -2.37^{+0.43}_{-0.46}\times 10^{-3}\text{eV}^2, \\ +2.46^{+0.47}_{-0.42}\times 10^{-3}\text{eV}^2, \end{cases} \end{array} \quad |U_L| = \begin{pmatrix} 0.77-0.86 & 0.50-0.63 & 0.00-0.22 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix}. \tag{4}$$

[*] E-mail: faguila@ugr.es
[**] E-mail: deblasm@ugr.es
[***] E-mail: adrian@ugr.es
[†] E-mail: jsantiago@ugr.es

The variation ranges correspond to 3σ errors, and the negative and positive Δm^2_{31} figures stand for inverted and normal hierarchy, respectively. There are excellent reviews on neutrino oscillation experiments [5] and global fits [6], which are in good agreement within the available precision. (We ignore LSND data [7].) Note that these experiments do not distinguish between Dirac and Majorana masses, because in both cases the neutrino charged gauge interactions are given by Eq. (3), and neutral gauge interactions also only involve left-handed (LH) neutrinos and are universal at lowest order [8] (see also [9]). In this scenario and in the absence of other light fields further new physics can be parameterized by the corresponding effective Lagrangian. Current limits on non-standard operators [10, 11] are presented in next section.

With the minimal SM fermion content neutrinos can have Majorana masses if we add Higgs triplets or we allow for higher order operators. This second case in particular includes the first one when the Higgs triplet is integrated out. At any rate there is lepton number violation (LNV), and neutrino masses result from the famous dimension five Weinberg operator [12] $\mathcal{O}_5$ after electroweak symmetry breaking

$$\frac{x_{\alpha\beta}}{\Lambda}\mathcal{O}_5^{\alpha\beta} = \frac{x_{\alpha\beta}}{\Lambda}\overline{(l_L^{\alpha})^c}\tilde{\phi}^*\tilde{\phi}^\dagger l_L^\beta \rightarrow \frac{x_{\alpha\beta}}{\Lambda}\frac{v^2}{2}\overline{(\nu_L^\alpha)^c}\nu_L^\beta\ , \quad m_{\nu i} = -U^\dagger_{Li\alpha}\frac{x^\dagger_{\alpha\beta}}{\Lambda}v^2 U^*_{L\beta i}\ . \tag{5}$$

In this case the tiny neutrino masses are due to the very small operator coefficients $x_{\alpha\beta}/\Lambda$ multiplying $\mathcal{O}_5^{\alpha\beta}$, which are so minuscule because $x_{\alpha\beta}$ are extremely small ($\sim 10^{-12}$ for $\Lambda \sim v$) or Λ is very large ($\sim 10^{14}$ for $x_{\alpha\beta} \sim 1$). In the latter case, as Λ is the effective scale in the Lagrangian expansion, all higher order effects from higher dimensional operators are negligible. Hence, the phenomenologically relevant situation at LHC is the first one, with new physics near the TeV scale and the dimensionless operator coefficients quite small on other grounds. In this set-up there are two possibilities, too: that the see-saw messengers generating $\mathcal{O}_5$ are near the electroweak scale, $M_{SSM} = \Lambda$, or that the new physics near this scale does not mediate the see-saw mechanism, $M_{SSM} \gg \Lambda$ but is related to it within a given model. We will discuss both cases in Section 3. As already emphasized, Majorana masses give the same neutrino oscillation predictions as Dirac ones in this minimal SM extension with only $\mathcal{O}_5$. But in this case the neutrino mass matrix is symmetric and $U_{R\beta i}$ in Eq. (2), which plays no rôle in neutrino oscillations, is equal to $U^*_{L\beta i}$ (see Eq. (5)).

Independently of the neutrino mass character any realistic model must reproduce the observed spectrum. Although many models can accommodate the values in Eq. (4), there is no compelling, simple and predictive theory of lepton flavor. But, as we emphasize in Section 4, in contrast with the quark sector lepton mixing is rather close to tri-bi-maximal mixing [13], what seems to indicate that a flavor symmetry slightly broken is at work.

2 Current limits on new neutrino interactions

Neutrino masses are bounded to be less than 0.1 eV [14], thus they are very small compared to other mass parameters in the theory, and in particular to the electroweak scale $v \simeq 246$ GeV. This makes them unobservable in laboratory experiments where the relevant energies are much larger, and generically in experiments sensitive to electroweak interactions ranging from muon decay to particle collisions at LHC. Thus, the question is if light neutrinos have further observable interactions beyond their masses. This can be answered considering the most general effective Lagrangian up to the relevant dimension to be fixed by the available experimental accuracy, and fitting it to present data. In general it is enough to go to the next order beyond the SM, typically up to dimension six. However, the analysis depends, as do the extra operators, on the fields assumed to be light and the symmetries preserved. Hence, it does depend on the Dirac or Majorana neutrino mass character, or more precisely on whether the effective Lagrangian involves or not RH neutrinos and on whether lepton number (LN) is conserved or not. As emphasized above, neutrino oscillations and then light neutrino masses and mixing are compatible with any neutrino mass character, Dirac or Majorana. Hence, we will discuss them in turn. The list of dimension six operators preserving the SM gauge symmetry and LN can be found in [15] for operators not involving RH neutrino singlets. As a matter of fact, the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry alone implies that all dimension

six operators involving only SM fields are LNC if they also conserve baryon number [16]. This list can be extended to include ν_R [17].

Neutrino masses are the only vestige of LNV within the SM if they originate from the Weinberg operator in Eq. (5). As the neutrino mass scale is so small, it is appropriate to assume that new physics parameterized by dimension six operators involving only SM fields or light RH neutrinos is LNC. Limits on those operators for LH neutrinos can be found in [10], being typically at the per cent level in definite models and near the expected sensitivity in neutrino oscillation experiments. Model independent bounds can be one order of magnitude larger. They are in general derived assuming only one new operator beyond the SM at a time. On the other hand, although requiring a precise cancellation (thus at least two new dimension six operators, besides the extension of the operator set to include light RH neutrinos), there is still a (small) window for new interactions with observable effects in a near detector at a neutrino factory [11].

3 See-saw signatures at LHC

Neutrino oscillations can not decide on the neutrino mass character without further interactions. However, if the neutrino mass generation mechanism is mediated by new particles near the electroweak scale, these and the associated mechanism could be established at the LHC. This has been often reviewed for see-saw neutrino masses [18–21]. There are three different tree level particle exchanges generating the see-saw operator in Eq. (5). The lepton and Higgs doublets can couple to heavy fermions transforming as singlets, N, or triplets, Σ, under $SU(2)_L$. These are known as see-saw of type I [22] and of type III [23], respectively. On the other hand, the two lepton doublets can couple to a scalar transforming as their symmetric product. This means an $SU(2)_L$ scalar triplet, Δ, what we refer to as see-saw of type II [24]. If there is no further new physics at the TeV than the see-saw mediators, the scalar and fermion triplets will be pair produced with electroweak strength at LHC for they transform non-trivially under $SU(2)_L \otimes U(1)_Y$. As a consequence, their discovery limits for an integrated luminosity of 30 fb^{-1} at 14 TeV are above half a TeV (see Table 1). This is quite different from the heavy neutrino singlet case

Table 1 LHC reach for see-saw mediators with an integrated luminosity of 30 fb^{-1} at 14 TeV. For a comparison with other heavy lepton SM additions giving multi-lepton signals see [25].

See-saw mediator	Discovery limit	Most significant signals	
Neutrino singlet N (D)	Difficult to observe	$\ell^\pm\ell^\pm\ell^\mp$	[26]
Neutrino singlet N (M)	Difficult to observe	$\ell^\pm\ell^\pm$, $\ell^\pm\ell^\pm\ell^\mp$	[26–29]
Scalar triplet Δ (NH)	600 GeV	$\ell^\pm\ell^\pm\ell^\mp$, $\ell^+\ell^+\ell^-\ell^-$, fewer ℓ	[28, 30]
Scalar triplet Δ (IH)	800 GeV	$\ell^\pm\ell^\pm\ell^\mp$, $\ell^+\ell^+\ell^-\ell^-$, fewer ℓ	[28, 30]
Fermion triplet Σ (D)	700 GeV	$\ell^\pm\ell^\pm\ell^\mp$, $\ell^+\ell^+\ell^-\ell^-$, up to 6ℓ	[26]
Fermion triplet Σ (M)	750 GeV	$\ell^\pm\ell^\pm$, $\ell^\pm\ell^\pm\ell^\mp$, up to 6ℓ	[26, 28, 31]

because N can only decay through its mixing with the SM leptons $V_{\ell N}$, suppressing the electroweak cross-section for single production by the corresponding quadratic factor $|V_{\ell N}|^2$. Current limits on this mixing, $|V_{eN\ (\mu N)}| < 0.05\ (0.03)$ [19,32,33], make them difficult to observe. The LHC reach and the main signals for the three types of see-saw mechanisms are gathered in Table 1. Fermion singlets and triplets can be Dirac (D) or Majorana (M), in which case events can be LNV as the samples to look at. On the other hand, the LHC potential for scalar triplets depends on the neutrino mass hierarchy, normal (NH) or inverted (IH), because this determines their coupling to τ leptons, which do not allow for an efficient scalar mass reconstruction [28].

Several comments are in order. The possibility of observing LNV events at large hadron colliders due to the production of heavy Majorana neutrinos was emphasized long ago [34], but in the decay of extra charged gauge bosons in left-right models [35]. This is still a viable possibility and heavy neutrinos are observable at LHC, for the reference luminosity and energy above, up to N masses $\sim$ 2 TeV for W_R masses up to ~ 4 TeV [19, 36]. Analogously, LHC can probe new neutral gauge boson masses up to 2.5

TeV and N masses up to 800 GeV for a leptophobic $Z' \to NN$ [37, 38]. Hence, heavy neutrinos transforming trivially under the SM can be observed at LHC but as products of new interactions. Otherwise, the large backgrounds [27, 39] for LNV and LNC signals and the small mixings with SM leptons make their significance too low for discovery. Present limits on these mixings follow by comparison with electroweak precision data and rare flavor changing processes [19, 32, 33], being more stringent in particular for muons due to the better determination of the CKM mixing matrix, in very good agreement with the SM prediction [1]. At any rate, there is some debate about the naturalness of so large mixings for a heavy Majorana neutrino because their size should be given by the see-saw value $\sqrt{m_\nu/\mathrm{TeV}} < 10^{-6}$. Although large mixings are parametrically possible [40], they still require some (accidental) symmetry [41]. Finally, although LNV signals, as same sign di-lepton events, have much smaller backgrounds than the corresponding LNC ones, in this case opposite sign di-lepton events, this does not mean that LNC signals are in general less significant when samples with larger lepton multiplicities are taken into account [19].

Alternatively, even if the interactions directly involved in the neutrino mass generation are too suppressed to manifest at large colliders, observables with a different physical origin can be related to neutrino masses in specific models. In such a case LHC could also give new insights on neutrino masses. For example, the flavor dependence of the neutralino decay rates to charged leptons can provide a determination of the corresponding neutrino mixing in specific supersymmetric models [42], or the observation of new vector-like lepton doublets decaying only to τ leptons can signal to a strongly coupled electroweak symmetry breaking sector, as recently shown in the context of a holographic composite Higgs model [43].

3.1 Lepton flavour violation

We can learn on neutrino physics from lepton flavor changing processes [44], even if we do not observe new resonances at LHC. These transitions require new lepton interactions not banished to very high energies to be sizeable. This is the case, for instance, of SM extensions tackling the hierarchy problem, like supersymmetric, Little Higgs, or extra dimensional models [45]. In general they predict lepton flavor violating transitions at an observable level in forthcoming experiments [46].

4 Models of neutrino masses

Let us comment on models of neutrino masses to conclude. In general they do accommodate their tiny scale compared with all other masses in the theory, their hierarchical splitting, and their mixing matrix quite close to tri-bi-maximal mixing [13],

$$U_L^{\mathrm{TBM}} = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & -\sqrt{3} \\ -1 & \sqrt{2} & \sqrt{3} \end{pmatrix} , \tag{6}$$

but there is no simple predictive model of such a pattern, on the other hand rather different from that for quarks, considered in general compelling. Lacking a theory of flavor, the challenge is often to make this pattern of neutrino masses compatible with a given class of models, for instance, constructed to solve the hierarchy problem or to unify the gauge interactions [47]. A popular solution is to realize the discrete symmetry A_4 on the leptonic sector [48], for it allows to enforce tri-bi-maximal mixing automatically, reducing the challenge to prove that the extended scalar sector breaks A_4 along the correct direction and that higher order corrections give small deviations from U_L^{TBM} [49].

In summary, there is still a lot of experimental and theoretical work ahead to have a satisfactory understanding of lepton masses and interactions. In particular, we expect to know if U_{L13} is different from 0 and CP violation in the leptonic sector is sizeable [1, 4–6].

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